Computer Aided Design for Smoke Management

This recently developed computer model can aid in evaluating the adequacy of a smoke management system in an atrium or covered mall

By James A. Milke, P.E., and Frederick W. Mowrer, P.E.

This is an overview of a recently developed computer model that can be applied as a design aid in evaluating the adequacy of a smoke management system in an atrium or covered mall. The algorithm is the result of an initial effort at adapting zone modeling for atrium applications.

Buildings containing large volume spaces such as atria present unique problems for smoke management system designers. A fire in the atrium or an adjacent communicating space has the potential to expose many people and a substantial amount of property to smoke. A rational design approach for smoke management systems entails evaluating the impact of smoke from an unwanted fire. Applicable analytical approaches for formulating smoke management system design requirements include algebraic equations and computer-based fire models.

A first order analysis can be conducted using algebraic equations such as those included within NFPA 92B.[1,2,3] The algebraic equations use a zone model which consists of dividing each compartment into an upper and lower zone. Uniform properties are assumed throughout each zone. In addition to the two zone assumption, application of the algebraic equations requires other assumptions pertaining to the fire and geometry of the space.

Using a computer-based approach, fewer simplifying assumptions are required, allowing more factors to be addressed. The most factors can be addressed by a field model that evaluates conditions at numerous points within a space. Field models require extensive input data, including flame plume and combustion parameters.[4] In the near future, execution of field models may become more practical. Computer-based zone fire models are also available, though they include the same assumption of layer homogeneity as in the algebraic equations. However, a computer-based zone model can relax most of the other assumptions made by the algebraic equations. Zone models are relatively amenable for design applications in terms of data and hardware requirements.

Development of the Computer-Based Zone Model

As a minimum, zone models applied as smoke management system design aids should address the issues identified in *Table 1.* These issues can be grouped into four categories. One category consists of output by the model, e.g. smoke layer characteristics. The next group includes environmental and building characteristics, e.g. factors to account for wind, natural vents and multiroom smoke propagation. Fire physics is the third group, including plume dynamics. The fourth category improves the usefulness of the algorithm as a design tool by providing initial estimates of the fan capacities.

Table 1. Desirable Aspects for a Model for Atrium Smoke Management Design

- Postion of smoke layer interface as a function of time.
- Temperature of the smoke layer as a function of time.
- Gas species concentration in the smoke layer as a function of time.
- Provision for mechanical ventilation systems
- Provision for natural ventilation
- Provision for multi-room smoke propagation
- Stratification effects of a linear ambient temperature profile between floor and ceiling.
- Effect of outside environmental conditions such as temperature and wind speed.
- Effect of confined flow conditions.
- Irregular cross-sectional compartment area.
- Wall and corner effects on smoke plume.
- Transport time lag of plume and ceiling jet.
- Hazard-based estimate of fan capacity

About the authors

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Following a survey of existing zone fire models, CCFM was selected as the best base model for adaptation.[3,5] CCFM included many of the desired aspects indicated in Table 1. Aspects absent from CCFM which had to be added include stratification effects of a linear ambient temperature profile between floor and ceiling, effect of confined flow, irregular cross-sectional compartment area, wall and corner effects on smoke plume, transport time lag of plume and ceiling jet, and hazard-based estimate of fan capacity. Since the basis for the six aspects have been reported throughout the literature, only a brief description of the changes associated with the aspects added to CCFM is provided here.

The resulting algorithm is labeled FMD.[3] The input requirements are similar to many other zone fire models. The geometry of the spaces must be provided along with openings to other spaces and ventilation characteristics. The fire size (as a function of time) and location must be specified. Characteristics of the fuel are necessary, including heat of combustion and yield fraction of combustion products need to be provided. Also required is a heat loss factor as well as ambient conditions and numerical parameters.

A pre-fire, ambient temperature variation can lead to the formation (stratification) of a smoke layer at some intermediate height, well below the ceiling of the compartment, thereby impacting the effectiveness of ceiling mounted fire or smoke detectors or automatic sprinklers. Because of the significant consequences of stratification, a routine for evaluating the potential for stratification is included. The maximum rise of a buoyant plume in a temperature varying environment is given as:[6,7]

$$z_{max} = 5.54 Q_c^{1/4} \left(\frac{dT_a}{dz}\right)^{-3/8} \quad (1)$$

where Z_{max} is the maximum height above fire source where stratification occurs (m), dT_a/dz is the ambient temperature gradient from floor to ceiling (K/m), and Q_c is the convective rate of heat release (kW).

The phenomenon of confined flow may occur in tall, slender spaces. Confined flow results in a significantly faster descent of the smoke layer interface and consequent more rapid filling of the space. Considering the initial plume rise from a fire, confined flow is achieved once the plume area equals the cross-sectional area of the atrium. The radius of a fire is approximately 0.2z, where z is the height above the top of the fire source. Equation (2) can be used to estimate the height at which plume cross sectional area is equal to the cross-sectional area of the space. This height is defined as an equivalent ceiling height is defined as the height at which confined flow is initiated:

$$z_{conf} = \sqrt{\frac{A_{space}}{0.20^2\,\pi}} = 2.82\sqrt{A_{space}} \quad (2)$$

where Z_{conf} is the height above fuel surface where confined flow is initiated (m) and A_{space} is the cross-sectional area of space (m^2).

The smoke layer interface is assumed to be at the point of contact between the plume and all of the walls estimated by equation (2). Smoke reaches this point within a time period approximated by the plume transport lag equation (see equation (5). Then, smoke is assumed to travel vertically toward the ceiling without any further entrainment, similar to flow in a duct. Once the space above the point of contact is filled, then the smoke layer interface descends similar to the descent of a layer from an unconfined plume with a ceiling height equivalent to the height of the point of contact.

Typically, a rectangular vertical cross section is assumed by zone fire models. In actuality, atrium spaces have a variety of shapes, as depicted in *Figure 1*. The shape of the cross section of the atrium is assumed to influence the smoke-filling process layer by modifying the volume of the upper portion of a cylindrical atrium. Considering the cross sections indicated in *Figure 1*, the volumes of the upper portion of the irregular atria are less than those for the rectangular atrium. The reduced volume allows the irregular space to fill more quickly than the rectangular space.

Consequently, the shape of the atrium is an important parameter. Consideration of a sloped ceiling configuration requires that the cross-sectional area of the space be expressed as a function of height. For the purposes of this algorithm, only sloped roofs are considered, i.e. step-like changes in cross section are not specifically addressed.

$$A(z) = \frac{dV}{dZ} = -\left[\frac{(H - z_l)(W_l - W_u)}{b} + W_u\right]\frac{Ab}{W_l} \quad (3)$$

where A(z) is the cross-sectional area at height, z(m^2), dV/dz is the room volume per room height (m^2), A is the horizontal cross-sectional area of space, at floor level (m^2) (A_{space} in equation (2)), W_l is the lower trapezoid width (m), W_u is the upper trapezoid width (m), H is the height of ceiling above floor (m), z_l is the smoke layer interface position above floor level (m), and b is the height of the trapezoidal area (m).

Location of the fire with respect to the walls and corners of a space can significantly influence the amount of air entrained into the smoke plume, thereby affecting the smoke production rate and consequently the speed of descent of the smoke layer within the space. Most zone models assume the fire is located in the center of the room, distant from any walls, producing an axisymmetric plume. This location provides the maximum amount of entrainment of air, available from 360° of the perimeter. Other possible plume configurations include those near a wall or an intersection of two walls, i.e. *wall plumes and corner plumes.* A wall plume exists when the fuel is located very near a wall and can entrain air

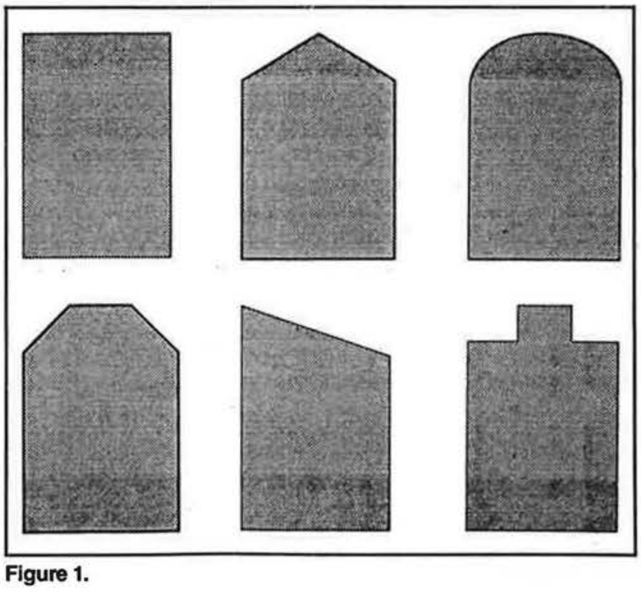

Figure 1.

only along approximately half of its perimeter. Similarly, a corner plume results from a fire located near the perpendicular intersection of two walls, only entraining air along approximately one-quarter of its perimeter.

The amount of air entrainment for wall and corner plumes can be estimated using the principle of reflection.[8,9] The principle of reflection is applied by adjusting the convective rate of heat release and mass entrainment by factors to account for location.[10] These two factors can be combined into one single location factor, kLF. The mass entrained into the plume for any location is given by the following general equation:

$$\dot{m} = C\dot{Q}^{1/3}\, z_l^{5/3}\, k_{LF}^{-2/3} \tag{4}$$

where m is the mass entrainment rate (kg/s) and k_{LF} is the fire location factor (1 for axisymmetric plumes, 2 for wall plumes and 4 for corner plumes).

The transport time lag can be an important addition because zone fire models typically assume that a smoke layer forms instantly. The transport time lag is the time delay associated with the time required for smoke to travel vertically from the vicinity of the flaming region to the ceiling, turn and travel horizontally to the enclosing walls. Subsequent to this time delay, smoke layer formation is initiated. In most applications involving zone fire models in spaces with low ceiling heights and small areas, the transport lag is very brief However, the transport lag is more significant spaces with tall ceiling heights and expansive areas because of the greater distance the smoke must traverse. An estimate of the total transport lag for a t^2 fire is given as:[11,12]

$$t_l = \frac{1.4r + 0.2H}{(A\alpha H)^{1/5}} \tag{5}$$

where t_l is the total transport lag (s), r is the radial distance from plume centerline to walls (m), A is a constant ($g/\pi_o c_{po} T_o \approx 0.028$ m^2/kg) and α is the fire growth coefficient.

The algorithm developed in this project estimates conditions based on the input provided, including the capacity of the exhaust fans. However, for designers applying the model, the exhaust fan capacity may be unknown and the focus of the analysis. Thus, an initial estimate of the exhaust fan capacity is needed based on the stated objectives for the system in terms of developing conditions within the atrium space, including lowest height of the smoke layer interface, maximum temperature increase for the upper smoke layer, maximum light obscuration in upper smoke layer, and maximum species concentration of prescribed fire gases in the upper smoke layer. The estimates are provided by algebraic expressions relating the conditions to smoke exhaust capacities based on a theoretical analysis[3].

Applications of FMD

Two applications are described in the paper. First, a comparison of the predictions from the algorithm with actual large scale experimental data is presented. Second, the algorithm is applied to demonstrate the capabilities of the model for use as a hazard analysis tool for a scenario involving multiple rooms.

The large-scale experiment referenced for the comparison was conducted in a space with horizontal dimensions of 30 × 24 m (98 × 78 ft) and a height of 26.3 m (86 ft). The fire consisted of a 3.24 m^2 (34.8 ft^2) methanol pool with a steady heat release rate of 1.3 MW with the mechanical exhaust operating. Mechanical exhaust with a capacity of 3.2 m^3/s (113 cfm) was actuated two minutes after ignition.

Even though an ignited flammable liquid pool quickly attains a peak heat release rate, an initial short period of time is required for the fire to reach the steady heat release rate, the heat release rate is ramped up to the steady values following a t-squared profile. A growth period duration of 30 s is chosen to represent the brief growth period in the computer simulation.[3]

A comparison of the predictions and data is presented in *Figure 2*. The actual time for the fan to reach capacity after actuation is unreported. In this application of the algorithm, the fan is assumed to reach capacity immediately after being actuated. The agreement between the predictions and the data for the smoke layer interface position is reasonable for the entire test. The transport lag associated with the experiment appears to be somewhat longer than expected. This may be due to the initial growth period in the experiment being longer than assumed.

One important capability of FMD is its ability to address situations involving multiple rooms. The multi-room capability is demonstrated through the five-room scenario depicted in *Figure 3*. Four "rooms" are open to the fifth room which is an atrium. Each of the four rooms is 1,000 m^2 (1,076 ft^2) in area. The room on the first floor has a ceiling height of 15 m (49 ft), otherwise the ceiling height of the other three rooms is 5 m (16 ft).

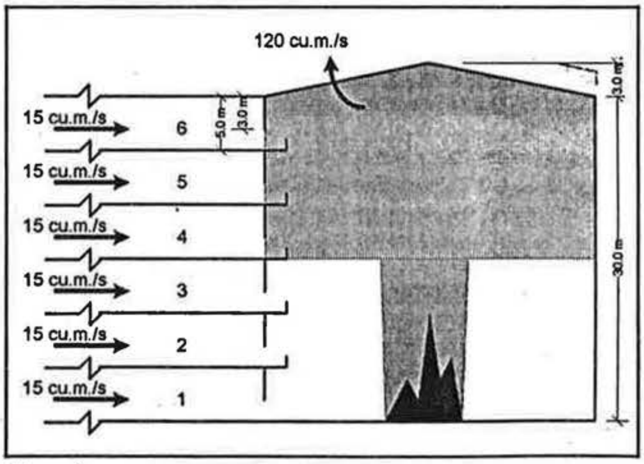

Figure 2.

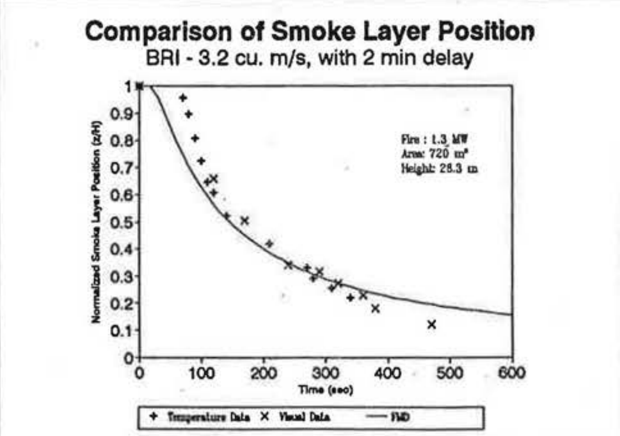

Figure 3.

Alternatively, this room on the first floor could also represent rooms on the first three floors, with the other rooms identified in the computer application to be located on the fourth, fifth and sixth floors. For discussion purposes, this latter interpretation is accepted for this example. In this manner, the computation time of the program can be reduced while examining conditions within seven rooms in a six story building with a simulation involving only five rooms on four levels.

The floor area of the atrium is 900 m^2 (9,687 ft). The atrium has a triangular roof with a height to the peak of 33 m (108 ft) above floor level. The triangular portion begins at a height of 30 m (98 ft) above the floor. As in other cases, the fuel is assumed to be red oak and has the same yield properties as applied before. 120 m^3/s (4,238 cfm) of mechanical exhaust is provided via a 10 m^2 (107 ft^2) duct located 28 to 30 m (92 to 98 ft) above the floor. As in the previous single-room case, make-up air is provided by a combination of forced supply and a natural vent. The 90 m^3/s (3,178 cfm) capacity of forced supply consists as distributed throughout the four communicating rooms, 45 m^3/s (1,589 cfm) from the room on the first floor and 15 m^3/s (530 cfm) from the rooms on the upper levels. All fans are actuated 300 s after ignition. A 1 m by 2 m (height) (3.2 ft × 6.6 ft) natural vent is provided between each communicating space and the atrium. A steady, 5 MW fire is assumed to be located on the center of the atrium floor.

An overview of the results of the application are provided in *Figure 4*, in terms of the position of the smoke layer interface in each room and the optical density of the smoke layer in each room. The smoke layer quickly descends in the atrium until the mechanical fans are actuated. Then, the smoke layer ascends to an equilibrium position within the next 300 s. Smoke layer positions continue to decrease temporarily in the communicating spaces, then reach an equilibrium position. Initially, this is caused by the smoke layer in the atrium being located below the opening to the communicating space. However, even after the smoke layer has been raised above the opening to the respective communicating space, the smoke layer appears to continue to descend. This apparent contradiction can be explained by referring to *Figure 4*, indicating the optical density of the smoke layer within each space. As indicated in this figure, the optical density quickly decreases to negligible levels after actuation of the mechanical smoke management system. The optical density decreases partially as a result of dilution within the communicating space. In addition, air might be entering into the communicating space from the warm lower layer in the atrium. Being that the temperature of the lower layer in the atrium is greater than the lower layer in the communicating space, the air from the lower layer of the atrium is introduced into the upper layer of the communicating space. Consequently, it appears to grow in size, yet the hazard associated with the upper layer in the communicating spaces decreases since the air from the lower layer does not contain any smoke.

Summary

Algebraic equation-based design aids are applicable for conducting a comprehensive, first order analysis of the adequacy of a smoke management system design for atria and covered malls. A computer-based method may be preferred in cases involving changes in geometry, time-dependent fire behavior or delayed actuation of the smoke management system. The examples included in this review demonstrate the advantages of FMD as compared to the algebraic equations. ■

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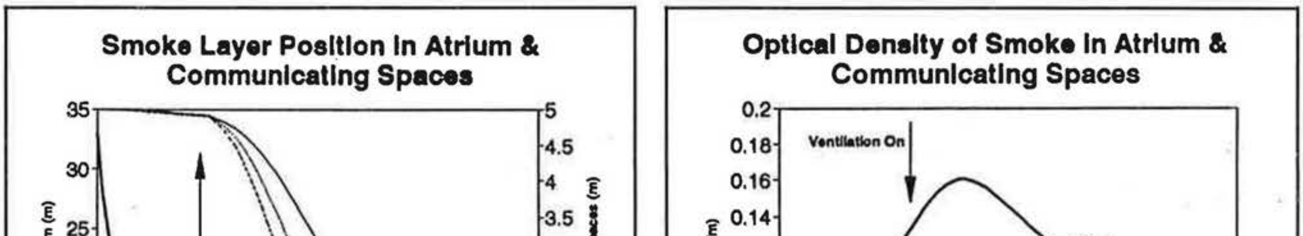

Figure 4.